

WL-TR-97-4006

**Resistivity of $\text{Fe}_{.49}\text{Co}_{.49}\text{V}_{.02}$ High Strength
Laminates from -73C to + 650 C**



Gerard K. Simon
Ronald E. Perrin
Melvin C. Ohmer
Timothy L. Peterson

Electromagnetic Materials and Survivability
Materials Directorate
3005 P Street, Suite 6
Wright-Patterson AFB OH 45324-7707

NOVEMBER 1996

FINAL DRAFT REPORT FOR 1 DEC 1995 - 30 NOV 1996

Approved for public release; distribution unlimited

**MATERIALS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AFB OH 45433-7734**

DTIC QUALITY INSPECTED 4

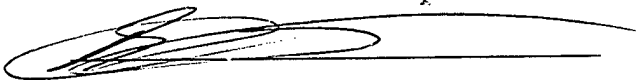
19970519 008

NOTICE

WHEN GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY GOVERNMENT-RELATED PROCUREMENT, THE UNITED STATES GOVERNMENT INCURS NO RESPONSIBILITY OR ANY OBLIGATION WHATSOEVER. THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA, IS NOT TO BE REGARDED BY IMPLICATION, OR OTHERWISE IN ANY MANNER CONSTRUED, AS LICENSING THE HOLDER, OR ANY OTHER PERSON OR CORPORATION; OR AS CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

THIS REPORT IS RELEASABLE TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS). AT NTIS, IT WILL BE AVAILABLE TO THE GENERAL PUBLIC, INCLUDING FOREIGN NATIONS.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.



Electronic & Optical Mat'ls Branch
Electromagnetic Mat'ls & Surv. Div.



ROBERT L. DENISON, Chief
Electronic & Optical Mat'ls Branch
Electromagnetic Mat'ls & Surv. Div.



WILLIAM R. WOODY, Chief
Electromagnetic Mat'ls & Surv. Div.
Materials Directorate

IF YOUR ADDRESS HAS CHANGED, IF YOU WISH TO BE REMOVED FROM OUR MAILING LIST, OR IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR ORGANIZATION PLEASE NOTIFY WL/MLPO, BLDG 651, 3005 P ST STE 6, WPAFB OH 45433-7707, TO HELP MAINTAIN A CURRENT MAILING LIST.

COPIES OF THIS REPORT SHOULD NOT BE RETURNED UNLESS RETURN IS REQUIRED BY SECURITY CONSIDERATIONS, CONTRACTUAL OBLIGATIONS, OR NOTICE ON A SPECIFIC DOCUMENT.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 30 Nov 1996	3. REPORT TYPE AND DATES COVERED Final Report 1 Dec 95 - 30 Nov 96		
4. TITLE AND SUBTITLE Resistivity of Fe _{.49} Co _{.49} V _{.02} High Strength Laminates From -73C to +650C		5. FUNDING NUMBERS PE: 62102F PR: 4348 TA: LA WU: BR		
6. AUTHOR(S) Gerard K. Simon, Ronald E. Perrin, Melvin C. Ohmer, Timothy L. Peterson/ all WL/MLPO				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Electromagnetic Materials and Survivability 3005 P St, Suite 6 Wright-Patterson AFB, OH 45433-7707		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Materials Directorate Wright Laboratory Air Force Materiel Command Wright-Patterson AFB OH 45433-7734 POC: Capt Gerard K Simon, WL/MLPO: 937-255-4474 x 3184		10. SPONSORING/MONITORING AGENCY REPORT NUMBER WL-TR-97-4006		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) Carpenter Hiperco® Alloy 50 HS is a recently developed iron-cobalt rolled sheet soft magnetic alloy (0.01% C, 0.05% Mn, 0.05% Si, 0.30% Nb, 1.90% V, 48.75% Co, 48.94% Fe) intended for commercial applications requiring high strength. Its physical, electrical and magnetic properties have not yet been reported over the operating temperatures of interest. This report addresses the resistivity testing of this alloy in .006" thick sheet product form (dry hydrogen annealed) and the subsequent conclusions. We tested the material in a cryogenic dewar from -73C to 27C and in a furnace to 650C. We found that at low temperatures, the resistivity of the material increased linearly. The coefficient of resistivity in this range was $2.9 \times 10^{-4} \text{ C}^{-1}$. At higher temperatures it increased faster than linear. The resistivity averaged 41.59 $\mu\Omega\text{-cm}$ at the lowest temperature, 43.76 $\mu\Omega\text{-cm}$ at room temperature and 68.48 $\mu\Omega\text{-cm}$ at the highest temperature. Analytic expressions for resistivity in the full temperature range of measurements are provided. Eddy current loss at room temperature is expected to be 590 W/lb for .006" sheet at 5000 Hz.				
14. SUBJECT TERMS Magnetic, Soft magnets		15. NUMBER OF PAGES 7		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OF REPORT unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT unclassified	20. LIMITATION OF ABSTRACT SAR	

ABSTRACT

Carpenter Hiperco® Alloy 50 HS is a recently developed iron-cobalt soft magnetic alloy (48.94% Fe, 48.75% Co, 1.90% V, 0.30% Nb, 0.05% Mn, 0.05% Si, 0.01% C) intended for commercial applications requiring high strength. Its physical, electrical and magnetic properties have not yet been reported over the operating temperatures of interest. This report addresses the resistivity testing of this alloy in .006" thick strip product form (dry hydrogen annealed) and the subsequent conclusions. We tested the material in a cryogenic dewar from -73C to 27C and in a furnace to 650C. We found that at low temperatures, the resistivity of the material increased linearly. The coefficient of resistivity in this range was $2.9 \times 10^{-4} \text{ C}^{-1}$. At higher temperatures it increased faster than linear. The resistivity averaged $41.59 \mu\Omega\text{-cm}$ at the lowest temperature, $43.76 \mu\Omega\text{-cm}$ at room temperature and $68.48 \mu\Omega\text{-cm}$ at the highest temperature. Analytic expressions for resistivity in the full temperature range of measurements are provided. Eddy current loss at room temperature is expected to be 590 W/lb for .006" sheet at 5000 Hz.

INTRODUCTION

Silicon steels currently dominate the world of soft magnetic materials. These materials provide acceptable saturation magnetizations with relatively low hysteresis loss for their applications. They are also moderately priced. This is the main driver for their success. Fe Co soft materials are not so common however, their high cost being the main reason for their comparative rarity. The iron-cobalts provide the highest saturation of any soft magnetic material and are currently available in 27% Co alloys, 36% Co alloys, and near 50-50 Fe Co alloys. Various elements can be added to boost resistivity, strength, and/or aid grain formation as necessary.

Carpenter Hiperco® Alloy 50 HS is a near 50-50 Fe Co alloy boasting a flux density of 23.0 Kgauss at 200 Oe. Carpenter claims its resistivity is 42 micro-ohms-cm at room temperature.

Another factor to be considered when selecting soft magnetic materials for use in a motor or generator, is

the resistivity of the alloy. This specification is necessary for estimating the eddy current losses to be expected in the operation of the motor or generator. Eddy current losses occur when the flux applied to a conductor induces a current flow in the material. The induced current diminishes the useful energy in the system and generates heat. Eddy current loss in laminates (see figure 1) is calculated for the low frequency case using the following equations¹²:

$$P_e = \frac{\pi^2 t^2 B^2 f^2}{6\rho} \left(\frac{W}{m^3} \right) \quad (1)$$

$$P_e \left(\frac{W}{lb} \right) = \frac{1}{(2.205)d} P_e \left(\frac{W}{m^3} \right) \quad (2)$$

In these equations, t is the laminate thickness in meters, B is the induction in Tesla, f is the frequency in sec^{-1} , ρ is the resistivity in $\Omega\text{-m}$ and d is the density in kilograms per cubic meter. Flux penetration is complete in situations where equations (1) and (2) are used. Precisely what is a high

* Hiperco is a registered trademark of CRS Holdings, Inc.

frequency and a low frequency is defined in terms of a frequency dependent penetration depth given by:

$$\delta = \sqrt{\frac{\rho}{\left(\frac{\pi f}{2}\right) \mu_0 \mu}} \text{ (meters)} \quad (3)$$

Here δ is the penetration depth in meters, μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ in SI or rationalized MKS units) and μ is the relative permeability. A representative value of μ was determined to be 1500 for this material by R. Strnat³ using a toroidal solenoid with a core consisting of laminate ring stacks as per ASTM A927/A927M-94⁴. Using $\mu=1500$, δ was calculated to be $0.0121626f^{-1/2}$ meters for this material. If 2δ is large compared to the laminate thickness, equations (1) and (2) apply as the flux completely penetrates. This is the case for Hiperco[®] Alloy 50 HS for frequencies of interest up to 5000 Hz as $\delta=.0068''$ for this situation (2δ is 2.2 times the laminate thickness). From equation (1) we see that eddy current loss relates directly to resistivity. The eddy current loss varies inversely with resistivity. One must remember, however, that eddy current loss is only a part of the total loss the material will experience. In any given situation its significance depends on whether it is larger or smaller than another primary source of loss, hysteresis loss.

According to Carpenter's data sheet⁵, the alloy's resistivity is 42 micro-ohms-cm at room temperature. However, for the application we are considering, we need to know the resistivity from -65C to 450C. This range corresponds to a cold start in Alaska up to hot engine temperatures. No information was available on the resistivity

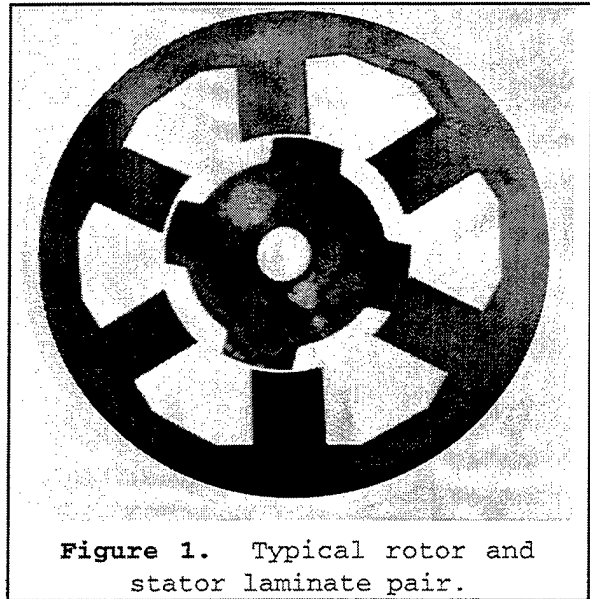


Figure 1. Typical rotor and stator laminate pair.

throughout this range. The goal of this testing was to determine the resistivity throughout the range and calculate a coefficient of resistivity.

METHODS, ASSUMPTIONS, AND PROCEDURES

The specimens used in this testing were .600 inches long, .100 inches wide and .006 inches thick. They were electric-discharge machined in the longitudinal, transverse and 45 degree orientations with respect to the rolling direction. We then divided the specimens randomly and annealed them at three different temperatures: 1300°F, 1328°F and 1350°F in dry hydrogen for one hour. This annealing procedure is one which produces high tensile strength material in the 110 ksi range as per the Carpenter data sheet. The specimens were designated: 1300F/90°, 1328F/0°, 1328F/45°, 1328F/90°, and 1350F/90° (anneal temp/orientation). A specimen of each anneal and orientation type was randomly selected for testing.

The samples had a thin coat of iron-oxide that was sanded off with 240 grit paper. The sanding also pro-

vided a rough surface for affixing contacts. To make contacts, gold was sputtered onto the strips. Next, we welded gold wires onto the contacts to make electrical connections with the specimens.

We mounted the specimens on a high accuracy test head and placed them into a cryogenic dewar cooled to -73°C with liquid nitrogen and helium. We measured each sample's resistivity in the forward and reversed directions while incrementally increasing the temperature to 27°C. Also, we performed two data runs with each sample. The first run was with no applied magnetic field. The second was with a 1 Tesla magnetic field applied perpendicular to the sample's plane. We had previously determined that the direction of the field did not affect the measured data.

Resistance was measured using similar methods to the four point method described in ASTM standard A712-75⁶. We took voltage measurements at five degree increments using a 50 mA current in the forward and reversed directions.

A Keithley 220 provided the current source while a Keithley 180 nanovoltmeter and 195A digital multimeter respectively measured the resistance voltage and checked the input current. A Hewlett Packard 3455A digital voltmeter measured the voltage from a platinum thermometer. A Danfysik magnet power supply applied the 1 Tesla field and National Instruments' Labview controlled the experiments.

We performed the high temperature portion of the testing in a dewar designed for use up to 700°C. The samples were heated in a nitrogen atmosphere by a silicon carbide heater. A Keithley 220 current source applied a 100 mA current in the forward and reverse directions.

Since magnetic fields did not affect the data appreciably in the low temperature testing, none were applied in the high temperature portion. A Keithley 619 multimeter measured the voltage at three degree increments as the temperature increased to 650°C. Additional readings were taken as the sample cooled to room temperature.

RESULTS AND DISCUSSION

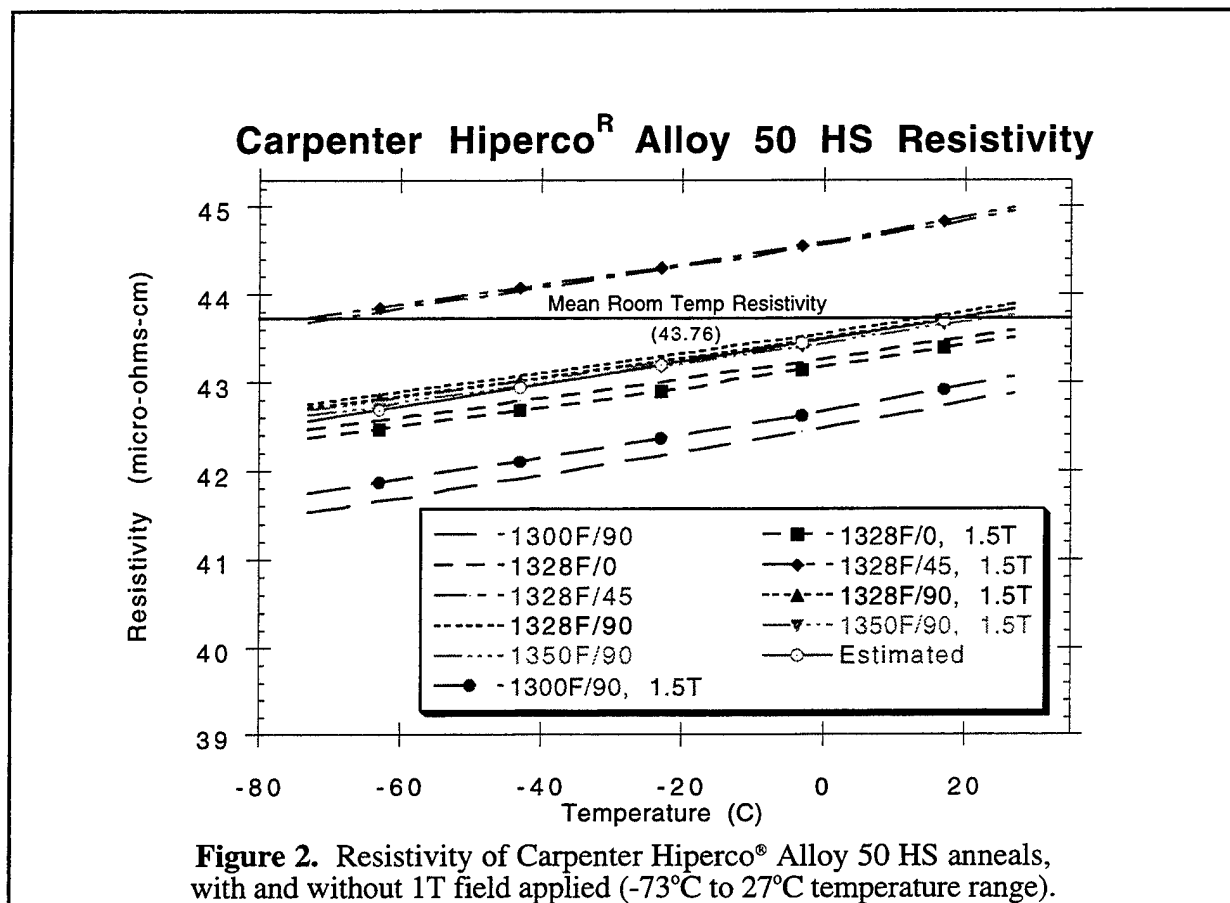
For the most part the results reinforced the available data on the alloy. The average resistivity with no field was 42.02 micro-ohms-cm at -73°C, 43.14 $\mu\Omega$ -cm at room temperature (22°C), and 69.24 $\mu\Omega$ -cm at 650°C. The room temperature value compares well to the nominal data sheet value of 43 $\mu\Omega$ -cm. With the magnetic field applied, the average room temperature resistivity rose

Table 1

Sample	Resistivity $\mu\Omega$ -cm		
	-73°C	22°C	650°C
1300F/90°	39.31	40.57	69.40
1328F/0°	41.69	42.66	68.88
1328F/45°	43.68	44.88	70.30
1328F/90°	42.75	43.82	71.11
1350F/90°	42.69	43.77	66.53
1 T field			
1300F/90°	39.44	40.68	-
1328F/0°	42.37	43.45	-
1328F/45°	43.73	44.91	-
1328F/90°	42.71	43.77	-
1350F/90°	42.62	43.70	-

Resistivity of FeCo samples
with respect to anneal temperature
and rolling direction

slightly to 43.32. Our overall average room temperature resistivity was 43.76 \pm 5% micro-ohms-cm and the coefficient of resistivity was .0003 C⁻¹. Table 1 shows the resistivities for each sample, with and without the 1T field. Figure 2 graphically displays the resistivity of each sample throughout the temperature range. Note that the resistivity in this range increases



quite linearly. Therefore, in this area one can calculate the resistivity within $\pm 5\%$ using⁷:

$$R_2 = R_1 \{1 + \alpha_1(t_2 - t_1)\} (\mu\Omega - cm) \quad (4a)$$

(for $t < 27^\circ\text{C}$)

$$R = 43.76 \{1 + .00029(t - 22)\} (\mu\Omega - cm) \quad (4b)$$

In figure 4 the resistivity vs. temperature over the full range of interest is plotted using equations (4b) and (5). Figure 2 shows a plot of the measured resistivities and the resistivity calculated using the average room temperature resistance as R_1 and room temperature, 22°C , as T_1 . We calculated the average coefficient of resistivity (α) to be $2.9 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$.

At high temperatures, the resistivity does not vary linearly

throughout the entire temperature range⁸. A discussion of this phenomenon is not attempted in this report. However, the data may be fitted directly using a polynomial to get a useful analytical expression.

$$R = 43.66 + .0034568t + .00005508t^2 (\mu\Omega - cm) \quad (5) \quad (\text{for } t > 27^\circ\text{C})$$

Or, following the approach of others, the temperature range can be subdivided into zones where a linear fit can be applied. Knowing the resistivity at the baseline temperature of each of these zones, one can calculate the resistivity with equation (4a). These zones range from -73°C to 27°C , 27°C to 200°C , 200°C to 400°C , 400°C to 600°C and 600°C to 800°C . We calculated the coefficient of resistivity within each of these linear zones.

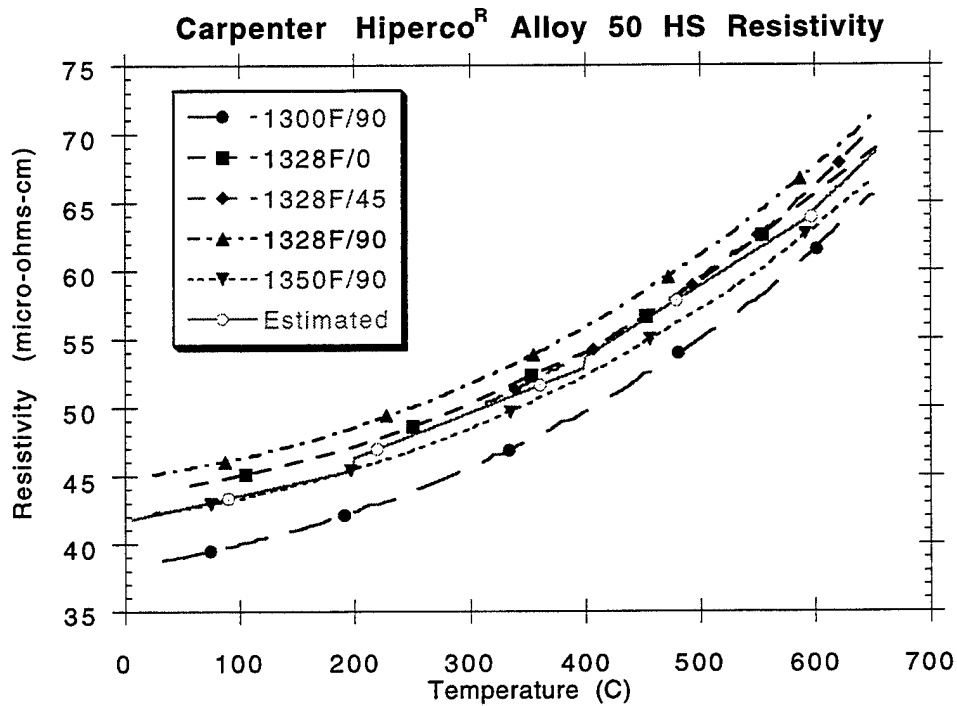


Figure 3. Resistivity of Carpenter Hipercor[®] Alloy 50 HS anneals with no fields applied (7°C to 650°C temperature range).

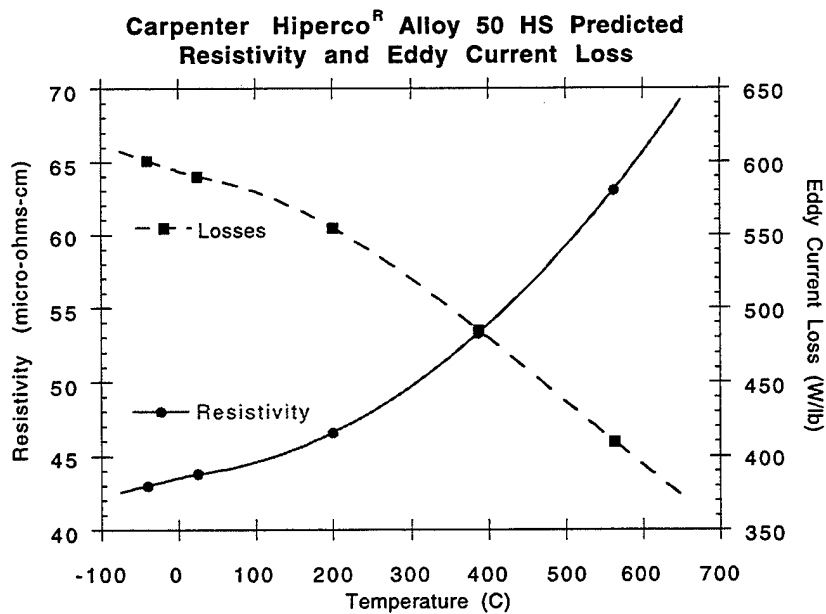


Figure 4. Predicted resistivity and eddy current loss at 5000 Hz of Carpenter Hipercor[®] Alloy 50 HS from -75°C to 650°C.

The baseline resistivities were obtained from experimental data. Although the results of this type of calculation will not yield precise figures, the result will be useful for approximating resistivities throughout a large temperature range. The expressions we provide in this work should prove to be useful in modeling eddy current losses in advanced motor/generator designs. Equation (1) for the case of $\rho=43 \mu\Omega\text{-cm}$, $f=5000 \text{ Hz}$ and $B=2.2 \text{ Tesla}$, a typical value for this material, gives a eddy current loss of 590 W/lb. The predicted eddy current loss vs. temperature, derived from our resistivity vs. temperature data, is shown in figure 4. Note that it is nearly a factor of two lower than room temperature at the engine operating temperature. The chosen frequency is characteristic of advanced airborne generator frequencies.

Table 2		
Temperature range (°C)	Coefficient of resistivity ($\alpha, \text{C}^{-1}, 10^{-4}$)	Baseline resistivity ($\mu\Omega\text{-cm}$)
-73 - 27	2.9	41.59
27 - 200	4.4	42.15
200 - 400	7.1	46.28
400 - 600	9.7	53.65
600 - 800	12.0	64.37

Mean coefficients of resistivity with respective resistivities

CONCLUSIONS

The resistivity of the samples was found to be independent of the anneal temperature and orientation. Table 1 depicts this fact. While it is possible that the range of anneal temperatures used for this experiment was not large enough to display a clear trend in the variation of the resistivities, what we see in this sampling is probably just a statistical distribution of the resistivities of about $\pm 5\%$. Using the information derived from this work, the resistivity can be estimated with a reasonable margin of error. Given the number of uncertainties in the design of magnetic devices, at least the resistivity can be better approximated using the expressions given in this work, leading to better eddy current loss estimates.

REFERENCES

- ¹ Chih-Wen Chen, *Magnetism and Metallurgy of Soft Magnetic Materials*, Dover Publications, Inc., New York, 1988. (see Eq. 4.88).
- ² Richard M. Bozorth, *Ferromagnetism*, D. Van Nostrand, New York, 1951.
- ³ KJS Associates Inc., *Private Communication*, Dayton.
- ⁴ *Standard Test Method for Alternating-Current Magnetic Properties of Toroidal Core Specimens Using the Voltmeter-Ammeter-Wattmeter Method*, Standard A927/A927M-94, American Society for Testing and Materials, Philadelphia, 1994.
- ⁵ Carpenter Technology, *Alloys*, Data Sheet 8-95/4M.
- ⁶ *Standard Test Method for Electrical Resistivity of Soft Magnetic Alloys*, Standard A712-75, American Society for Testing and Materials, Philadelphia, 1991.
- ⁷ John D. Kraus, *Electromagnetics*, McGraw-Hill, New York, 1953.
- ⁸ P.E. Kueser, D.M. Pavlovic, D.H. Lane, J.J. Clark and M. Spewock, *Properties of Magnetic Materials For Use In High Temperature Space Power Systems*, National Aeronautics and Space Administration Report No. NASA SP-3043, National Aeronautics and Space Administration, Washington D.C., 1967.